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REHEARSAL STRATEGIES DURING MOTOR-SEQUENCE LEARNING IN OLD AGE: EXECUTION VS MOTOR IMAGERY [1,2]

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Summary.—Motor imagery and action-based rehearsal were compared during motor sequence-learning by young adults ($M=25$ yr., $SD=3$) and aged adults ($M=63$ yr., $SD=7$). General accuracy of aged adults was lower than that of young adults ($F_{1,28}=7.37$, $p=.01$) even though working-memory capacity was equivalent in the two groups. Motor imagery and rehearsal by action increased accuracy in both age groups, compared with minimization of opportunity for rehearsal ($F_{1,28}=30.95$, $p<.001$), but no interaction was found with age group, which suggests that young and aged adults were equally capable of motor imagery and action-based rehearsal. It was assumed that differences in performance between young and aged participants related to the formation of mental representations of sequences and integration of new elements into these representations rather than the capacity for motor imagery or rehearsal by action *per se*. The current study was exploratory and involved a relatively small sample of 15 participants per age group. Caution must be taken when considering the results.

Learning and maintaining motor skills are important in our daily lives. As we grow older, we are confronted with cognitive deteriorations (Salthouse, 1990, 1996, 1998; Verhaeghen, Vandenbroucke, & Dierckx, 1998; Castel & Craik, 2003; Fisk & Sharp, 2004), find ourselves more challenged by a wide variety of explicit memory tasks (e.g., Hultsch & Dixon, 1990), and face substantially impaired sensorimotor control (e.g., Siedler & Stelmach, 1995), leading to general alternations in motor skill acquisition. Indeed, aged adults show reduced speed and accuracy in motor learning (e.g., Durkina, Prescott, Furchtgott, Cantor, & Powell, 1995).

An interesting question on age-related deterioration of motor learning is whether deterioration is general or specific in nature. For instance, some studies report unaffected implicit or procedural learning by aged adults, while explicit learning is compromised (Harrington & Haaland, 1992;

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Twitchell, Cherry, & Trott, 1996; Ghilardi, Eidelberg, Silvestri, & Ghez, 2003). As such, motor learning by means of implicit mechanisms might be more effective for those of greater age than motor learning based on explicit strategies. The differentiated effect of age on implicit and explicit learning illustrates that insight into the specificity of age-related deterioration could be of vital importance to the development of effective motor-learning programs, for instance, in rehabilitation.

The current study was an exploratory study on action execution and motor imagery as a means of rehearsal during acquisition of a motor sequence and their relation to natural aging. A common example of a type of task in daily life during which execution of action plays a role might be learning a dance in which one could be instructed to perform movements along with a teacher or to first observe the teacher's movements and then perform them. In the first situation, learning and rehearsal are supported by executing the action, while the second situation requires internal simulation of movements, known as motor imagery.

Motor imagery can be defined as a mental state during which one replicates an action without any apparent motion of the limbs involved in the actual execution of the same action (Skoura, Charalambos, Vinter, & Pozzo, 2005). It is known that motor imagery can be used to acquire motor skills (e.g., Kosslyn, Behrman, & Jeannerod, 1995). Research on the neural and functional levels of motor imagery indicates that motor imagery is not a unitary neural function but has a complex underlying structure, arising through constellations of distinct neural processes (Posner & Peterson, 1990; Kosslyn & Koenig, 1992; Dror & Kosslyn, 1994). Further, it seems that roughly the same neural networks are activated when a subject executes or imagines an action (e.g., Decety, 1996). This phenomenon of similar neural activation during execution of action and action imagery is also known as the simulation theory (Jeannerod, 2001). Interestingly, the simulation theory has been supported for young adults, but little information is available on this relation to natural aging.

Aged adults are known to exhibit stronger and more extended neural activation across a variety of memory tasks and motor tasks than young adults, which is supposed to reflect compensation for age-related declines in neural functioning and recruiting of specialized neural mechanisms (Cabeza, 2002; Logan, Sanders, Snyder, Morris, & Buckner, 2002; Reuter-Lorenz, 2002; Buckner, 2004). It is possible that the changes in neural activation-patterns of aged adults compromise the orchestration of processes involved in motor imagery of actions, resulting in a reduced ability for motor imagery. An interesting question is whether the ability to use a rehearsal strategy based on motor imagery deteriorates with age compared to use of a rehearsal strategy based on execution of action.

A sequence-learning task was employed during which young and aged participants acquired and replicated sequences of simple goal-directed hand or arm movements. Sequence learning was used because it allowed easy and discrete measurements of learning and performance and is an important part of motor skill acquisition (e.g., Rhodes, Bullock, & Verwey, 2004). The task consisted of experimental blocks during which acquisition of sequence was either supported by (a) motor imagery, (b) execution of the action, or (c) neither.

Based on age-related cognitive deteriorations (Salthouse, 1990, 1996, 1998; Verhaeghen, *et al.*, 1998; Castel & Craik, 2003; Fisk & Sharp, 2004), it was expected that young adults would generally outperform aged participants.

Next, both young and aged adults were expected to show increased correct replication of sequences following both motor imagery and execution of action, above that noted when no opportunity for rehearsal was present.

The final and most important hypothesis was based on the simulation theory of motor imagery (Jeannerod, 2001) and the relatively increased and more distributed neural activity in aged adults during common task performance (Cabeza, 2002; Logan, *et al.*, 2002; Reuter-Lorenz, 2002; Buckner, 2004). Describing similar neural activation during imagery and execution of action, rehearsal during these should give the same results in the younger participants. For the older participants, on the other hand, relatively increased and more distributed neural activity during common task performance was hypothesized as possibly interfering with the distributed and orchestrated nature of motor imagery. If so, rehearsal by motor imagery should result in less successful replication of sequences than rehearsal by older participants executing the action.

Method

Participants

A total of 30 healthy volunteers participated in two age groups: young adults, ages 20–30 years (15 participants, M age 25 yr., $SD=3$; 7 men, 8 women), and aged adults, ages 50–75 years (15 participants, M age 63 yr., $SD=6$; 8 men, 7 women). The number of participants was based on *a priori* sample-size analysis ($\alpha=.05$, $\beta=0.2$) with a medium effect size (power = .80) and earlier experimental research on aging and motor learning (e.g., Zervas & Kakkos, 1991; Stefan, Cohen, Duque, Mazzocchio, Celnik, Sawaki, Ungerleider, & Classen, 2005; Heuninckx, Wenderwoth, Debaere, Peeters, & Swinnen, 2005; Lawson, Guo, & Jiang, 2007). None of the participants reported a history of neurological or other medical problems which may have interfered with the aim of the study. This study was approved by the local medical ethics committee.

Procedure

Participants were seated in front of a computer touch-screen (ELO Entuitive 1825 L, 18-in. desktop—IntelliTouch), placed at an angle of approximately 30°. The sequence-learning task was very similar to the 1980s memory-game of "Simon." Four colored squares were shown on the touch screen, arranged in a centered 25- × 25-cm, 2 × 2 matrix on a black background. The colors of the squares were (clockwise, starting top left) red, yellow, blue, and white. Each square could be highlighted individually by the computer so that sequences of squares lighting up could be formed. Sequences were generated randomly, but no square was illuminated twice in a row.

Each square of the sequence was highlighted for 300 msec., and the interval in between the highlighting of squares was also 300 msec. After a sequence had been presented, participants had to replicate the sequence by touching the squares in the perceived order. They were prompted to do so by the appearance of three dots at the bottom of the screen just below the four squares. A square was highlighted for 100 msec. on touch. The three dots remained visible until participants had touched a number of squares equal to the length of the presented sequence.

Sequences were presented stepwise, increasing in length with each step. First, one square was highlighted, then a second square was added so that two squares were highlighted one after another, then a third one was added and so on, until finally the sequence had reached a length of 10 squares. The overall goal of the task was to replicate this final 10-step sequence successfully.

After the sequence had reached a length of 10 steps, and participants had responded by reproducing this 10-step sequence, a new sequence started with a "length" of one square. This was considered a trial. Within the trials, the time between the increases in sequence length was 1,000 msec. Between trials the screen turned black for 1,000 msec. Four experimental blocks, each 10 trials, were used. The order of block presentation was randomized for each participant.

Two of the blocks were used to distinguish the effect of motor imagery from that of action execution during rehearsal: the action-based rehearsal block, and the motor-imagery block.

Action-based rehearsal block.—When using action execution during rehearsal, participants replicated the sequences each time the sequences had grown in length. This way, when participants finally replicated the 10-step sequence, they had rehearsed its intermediate steps by action execution.

Motor-imagery.—During the motor-imagery block, rehearsal used motor imagery rather than action execution. Participants did *not* replicate the sequence by action execution each time it increased in length. Instead, they

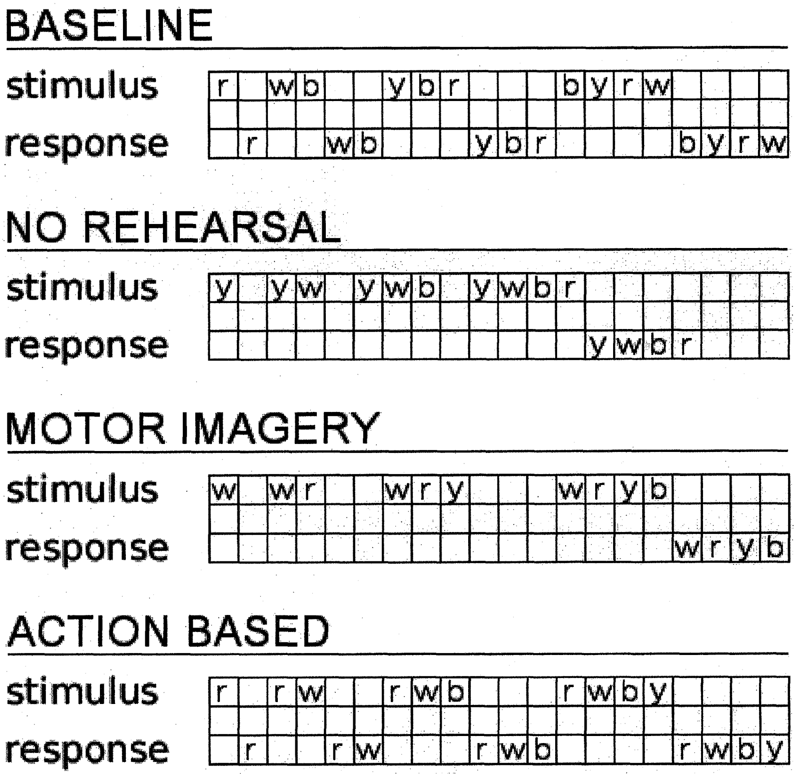

FIG. 1. Schematic representation of the relation between stimulus and response during the 4 task blocks. Letters code the square colors (r = red, y = yellow, b = blue, w = white) for stimulus and response. As an example, the final sequence length in this figure is set to 4. In the task this was set to a length of 10 squares. Order of blocks was randomized for each participant during measurements.

were given time to rehearse the sequence mentally, following each time the sequence had grown in length. The time interval for motor imagery increased as the presented sequence grew longer by one square, i.e., 600 msec. was added to the time interval for motor imagery. This 600-msec. interval was based on extensive pilot studies. Participants were explicitly instructed to use the time interval for motor imagery. After presentation of the final 10-step sequence, participants were prompted to replicate the sequence. This way, the replication of the 10-step sequence was rehearsed using motor imagery.

A task structure as described above has other potential determinants of performance besides rehearsal by action or imagery. Of the most important are working-memory capacity of both age groups and the sensitivity to the repeated presentation of the sequences as they grow in length, which could be taken as a form of rehearsal.

To account for the effect of repeated and incremental presentation of the lengthening sequences, a *no-rehearsal block* was used. Structure of this block resembled the motor-imagery block in that a sequence was followed by a time interval, after which the sequence was repeated and increased in length by one square. Contrary to the motor-imagery block, however, the time interval was kept at a constant length of 1,000 msec. This way, opportunity for rehearsal by participants was minimized. Of course, a small amount of rehearsal might still have been possible, especially during the first few steps of the sequence, but rehearsal should be minimized relative to the motor-imagery block and action-based rehearsal block.

Finally, the effect of working-memory capacity on successful replication of the sequences was assessed using a *baseline block*. First one square was highlighted, after which participants were prompted to touch that square. Next, they were presented a series of two highlighted squares, after which they had to touch the first and then the second square, and so on. Although sequences increased in length, these changed with each step they grew longer. So the final sequence of 10 squares was completely independent of its preceding sequences of 1, 2, 3, 4, 5, 6, 7, 8, and 9 steps in length.

Before commencing an experimental block, participants were allowed to practice until they fully understood what was expected of them and could verbally repeat this for the experimenter. Participants were instructed to respond as fast and accurately as possible during all experimental blocks, using the dominant hand (self-reported). The order of block presentation was randomized for each participant.

Data Analysis

The overall goal of the task was to replicate successfully the final 10-step sequence at the end of each trial. Maximum correct replication was 10 of 10 squares, resulting in an accuracy value of 1, and the minimum was, of course, 0. Mean values of 10 trials in each block were taken as a measure for block accuracy. Multiplying block accuracy by 100 yielded percentage accuracy scores. The measure of accuracy was based on exact replication of the sequences, i.e., touching exactly the correct squares in exactly the right order. Hypothetically if participants were presented the sequence Y R Y B W B Y and omitted the third item during replication as Y R B W B Y W, the score would be 5 errors.

Experimental blocks were compared using a one-way repeated-measures analysis of variance, containing one between-participants factor with four levels (blocks) and one within-participants factor with two levels (age group), using repeated contrasts: the baseline block vs priming block, priming vs motor imagery, and motor imagery vs action execution.

The software was Matlab (v7.1.0.246, The MathWorks, 2005) and Excel (v10, Microsoft Co., 2002) for analysis, and SPSS (v11.01, SPSS, Inc., 2001) for statistics.

Results

Shown in Table 1 are mean percent accuracy, standard deviations, and *SEM* for mean block- and overall scores, for young and aged adults.

TABLE 1

Mean Accuracy, Standard Deviations, and Standard Error of Mean (%) For Individual Blocks and Overall Scores For Young and Aged Adults (*n*s = 15)

Block	Accuracy		*SD*		*SEM*	
	Young	Aged	Young	Aged	Young	Aged
Baseline	44.1	45.1	9.0	8.2	2.3	2.1
No Rehearsal	67.8	58.0	13.4	7.0	3.5	1.8
Motor Imagery	79.4	67.9	9.6	12.0	2.5	3.1
Action-based	76.5	63.5	13.5	11.3	3.5	2.9

According to the first hypothesis young adults were expected to outperform the aged adults. Tests of between-subjects effects gave an effect of blocks ($F_{1,28} = 7.37$, $p = .01$), indicating a general difference in accuracy between the two age groups, where aged adults were generally outperformed by the young.

Next it was hypothesized that both young and aged adults would show increased accuracy after rehearsal using both motor imagery and action execution, compared to scores without opportunity for rehearsal. Tests of within-subject contrasts showed a significant effect of block on accuracy between the no-rehearsal block and the motor-imagery block ($F_{1,28} = 30.95$, $p < .001$) with no interaction of block and age group ($F_{1,28} = .19$, $p = .67$). Not only did both age groups increase accuracy with motor imagery, but absence of an interaction between block and age group also indicated that young and aged adults were equally capable. Next, no main effect ($F_{1,28} = 3.40$, $p = .08$) or interaction ($F_{1,28} = .15$, $p = .70$) was found between the motor-imagery block and action-based rehearsal block, which in turn implicated a significant difference between the no-rehearsal block and the action-based rehearsal block. Compared to the no-rehearsal block, both young and aged adults increased their mean accuracy after motor-imagery and action-based rehearsal, and both age groups were equally capable.

Finally, young adults were hypothesized to show no difference in accuracy between the motor-imagery block and action-based rehearsal block, while aged adults *would* show reduced accuracy during the motor-imagery block. This interaction expected between age group and block was not found ($F_{1,28} = .15$, $p = .70$), and no main effect for block was evident ($F_{1,28} = 3.40$, $p =$

.08). Although aged adults showed less accuracy during motor-imagery and action-based rehearsal, accuracy during motor imagery did not differ from accuracy during action-based rehearsal within the age groups.

In addition, results showed two unexpected findings worth mentioning. First, Table 1 suggested no difference in percent accuracy during the baseline block between young (44%, $SD=9\%$) and aged adults (45%, $SD=8\%$). An independent-samples t test showed no significant difference between young and aged adults during the baseline block. Second, the baseline block vs no-rehearsal block contrast showed an effect of experimental block ($F_{1,28}=85.12$, $p<.001$) as well as an interaction of block and age ($F_{1,28}=7.50$, $p=.01$).

Discussion

In accord with the first hypothesis as well as previous observations (Hultsch & Dixon, 1990; Salthouse, 1990, 1996, 1998; Durkina, *et al.*, 1995; Siedler & Stelmach, 1995; Verhaeghen, *et al.*, 1998; Castel & Craik, 2003), aged adults were generally outperformed by young adults. More specific, young adults showed better mean percent accuracy than aged adults when no opportunity for rehearsal was present, when rehearsal was based on motor imagery, and when rehearsal was based on action. During the baseline block, however, no difference in accuracy was found between age groups.

It is argued that the key component of the baseline block was working-memory capacity, at least relative to the no-rehearsal, motor-imagery, and action-based rehearsal blocks. This is consistent with a study by Humes and Floyd (2005) who used a similar kind of memory task. Because accuracy was equal for both age groups in the baseline block but differed in favor of young participants during the no-rehearsal, motor-imagery, and action-based rehearsal blocks, it is suggested that (cognitive) processes imposed upon stored items were affected by age rather than differences in short-term storage. This differentiated age effect on memory is in accord with studies reviewed by Salthouse (1990), and with an age-related decline in the use of meta-cognitive strategies to assist in memory performance (Sanders, Murphy, Schmitt, & Walsh, 1980; Witte, Freund, & Brown-Whistler, 1993).

According to the second hypothesis, both young and aged adults were expected to show increased accuracy with rehearsal, either by motor imagery or action execution, relative to when no opportunity for rehearsal was present.

Before discussing results on the second hypothesis, two critical points have to be clarified concerning the no-rehearsal block. First, the incremental presentation of sequences during the no-rehearsal block could be taken as a form of rehearsal. While this is true, of course, it is important to note that incremental presentation of sequences was also present during the motor-imagery block and action-based rehearsal block. It may, therefore, be argued that the incremental presentation of sequences should not pose a confounding thread as far as block comparison is concerned, and that differences in accuracy between the no-rehearsal block and rehearsal blocks were related to either motor imagery or action execution. Second, one could argue that the short constant time interval of 1,000 msec. following each incremental step in the no-rehearsal block could be used as an opportunity for rehearsal, especially in the early steps of the sequence. To counteract rehearsal in the 1,000-msec. time interval, participants were explicitly instructed to avoid the use of the time interval for rehearsal. While the time interval might still have been used for rehearsal, analysis clearly indicated lower accuracy for both age groups during the no-rehearsal block compared to rehearsal by motor imagery and executing the action. It may be argued then that, while some opportunity for rehearsal remained present during the no-rehearsal block, the opportunity for rehearsal relative to motor-imagery and action-based rehearsal was minimized.

Taking into account the two critical notes concerning the no-rehearsal block (see previous paragraph), results support the second hypothesis. First, increase in accuracy was found in the motor-imagery block relative to the no-rehearsal block in both age groups, indicating that both age groups actually used the rehearsal time for motor imagery. In addition, it is very interesting to note the absence of an interaction of experimental block and age group between the no-rehearsal block and motor-imagery block. Not only did both age groups use motor imagery to improve accuracy, but these groups were also equally capable of doing so.

Second, no differences in accuracy were found between the motor-imagery block and action-based rehearsal block. In light of the second hypothesis, the absence of differences between motor imagery and rehearsal by action illustrates that both age groups improved accuracy with action-based rehearsal relative to the no-rehearsal block during which opportunity for rehearsal was minimized. Again, the absence of an interaction between block and age group indicated that both young and aged adults were equally capable of using action-based rehearsal to increase accuracy.

Finally, the most important point of the absence of differences between motor imagery and rehearsal by action related to the third hypothesis. It was hypothesized that relatively increased and more distributed neural activity during common task performance in aged adults might interfere with the distributed and orchestrated nature of motor imagery. While young adults were expected to show similar accuracy after motor imagery and rehearsal by action, aged adults were expected to show lower accuracy when rehearsal was based on motor imagery. In other words, an interaction of block and age group was expected between motor imagery and rehearsal by action. However, the absence of such an interaction illustrates that, within each age group, rehearsal by motor imagery and action execution were equally effective.

It seems, then, that rehearsal by motor imagery and executing action yield similar accuracy scores within age groups when learning a motor sequence. Furthermore, the relatively lower accuracy of aged adults during both rehearsal blocks did not seem to be related to the adults' capacity for motor imagery or action-based rehearsal *per se*. Rather, the differentiation in accuracy between age groups was found on comparing the no-rehearsal block with the baseline block, in which the increased accuracy during the no-rehearsal block for young adults was twice that of the aged participants. Further absence of interactions suggests this block comparison contained a key component sensitive to aging, independent not only of working memory capacity but also of ability to use motor imagery or execution of action by rehearsal.

Just as working memory was the key component of the baseline block and rehearsal by motor imagery and action execution that of the rehearsal blocks, one may argue that the key component of the no-rehearsal block was construction of mental representations of sequences and integration of new elements into these representations, a phenomenon generally known as mental synthesis (Pearson & Logie, 2000). In accord with the literature, studies on learning and aging have shown marked deterioration of mental synthesis in the age-related decline in learning, which becomes evident after about age 60 (Herman & Coyne, 1980; Ludwig, 1982; Salthouse, 1987).

Please note that the current study was exploratory so caution must be taken in generalizing the results. First, the types of movements used were relatively simple and embedded in sequences of rather abstract stimuli. It is therefore difficult to rule out the possibility that task performance was a measure of learning of spatial sequences rather than of motor learning. Follow-up studies by which perceptual rehearsal could be distinguished from motor imagery would be required, or the use of more complex motor actions. Second, the sample size of 15 participants per age group has to be acknowledged as relatively small in this exploratory study. Although the chosen size was based on an *a priori* sample-size calculation, and earlier experimental research on aging and motor learning (e.g., Zervas & Kakkos, 1991; Heuninckx, *et al.*, 2005; Stefan, *et al.*, 2005; Lawson, *et al.*, 2007), caution in generalization of results is in order.

The main focus of this study was the role of action-based rehearsal and motor imagery during motor-sequence learning in old age. Taking into account the limitations and critical notes, it was concluded that no age-related difference was found between motor imagery and rehearsal by action. Although these aged adults performed more poorly than young adults during both blocks, these differences in percent accuracy between age groups seemed based on a reduced capacity of the aged adults to form mental representations of the sequences and to integrate elements into these representations rather than their capacity for motor imagery or rehearsal by action.

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